

Anomalous Single Production of the Fourth Generation Quarks at the LHC

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Abstract

Possible anomalous single productions of the fourth standard model generation up and down type quarks at CERN Large Hadron Collider are studied. Namely, $pp \rightarrow u_4(d_4)X$ with subsequent $u_4 \rightarrow bW^+$ process followed by leptonic decay of W boson and $d_4 \rightarrow b\gamma$ (and its h.c.) decay channel are considered. Signatures of these processes and corresponding standard model backgrounds are discussed in detail. Discovery limits for quark mass and achievable values of anomalous coupling strength are determined.

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Keywords: Anomalous interactions; colliders; fourth generation quarks.

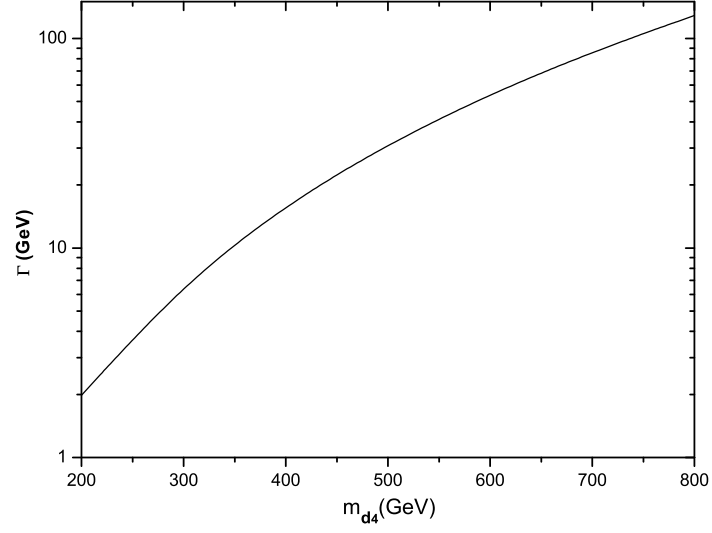
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I. INTRODUCTION

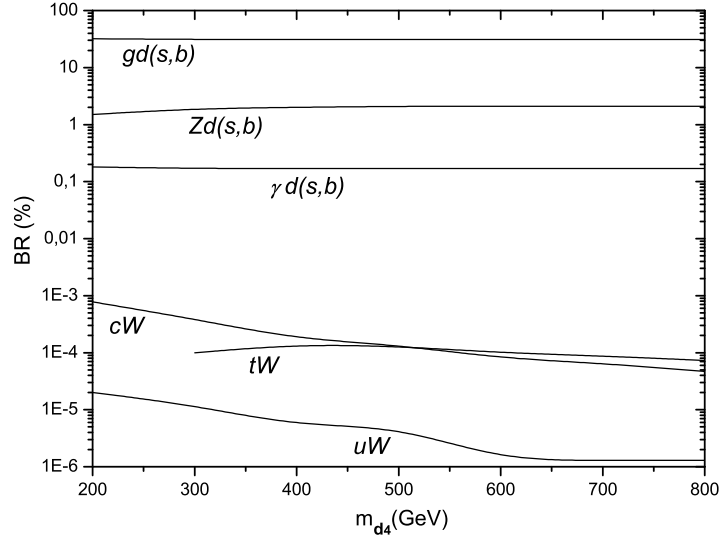
The number of fundamental fermion generations is not predicted by the Standard Model (SM). This number is restricted from below with LEP I data on invisible decays of Z boson as $n_g \geq 3$ [1]. On the other hand, the asymptotic freedom of QCD enforces the number of generations to be less than 9. The recent precision electroweak data are equally consistent with existence of three or four SM generations [2, 3, 4].

The flavor democracy is a natural hypothesis in the framework of SM as well as a number of models dealing with new physics (see review [5] and references therein). The flavor democracy hypothesis in SM predicts the existence of the fourth SM generation [6, 7, 8]. Tevatron experiments give 250 GeV of lower bound on the mass of the fourth generation quarks [9]. However it does not fix the masses and mixings of the new fermions. Another prediction of the flavor democracy is the masses of the fourth generation fermions to be nearly degenerate and lie between 300 and 700 GeV, whereas, the masses of known fermions belonging to lighter three generations appear due to small deviations of the democracy [10, 11, 12]. The last value is close to the upper limit on heavy quark masses, which follows from partial-wave unitarity at high energies [13]. The quark masses and Cabibbo Kobayashi Maskawa (CKM) matrix for certain parametrization of mass matrix are given in Refs. [10, 11]. Ref. [12] gives both masses and CKM matrix (Maki Nakagawa Sakata (MNS) matrix for leptons) for both quarks and leptons for another parametrization.

A new era in High Energy Physics will be opened with the construction of TeV scale colliders [14]. Obviously, TeV energy colliders are needed for discovery of the fourth SM generation fermions. The first of the such colliders is the Large Hadron Collider (LHC) with 14 TeV center of mass energy. The fourth generation quarks is predicted to be copiously produced in pairs at the LHC [15, 16]. Recently, this process is proposed as the best scenario (after Higgs) for discovery at the LHC [17, 18, 19]. Also, a serious contributions of anomalous interactions for the production of the fourth generation fermions can be expected. Such anomalous interactions seems to be quite natural due to large masses of the fourth generation fermions (see argumentation for anomalous interaction for t quark presented in ref. [20]). These anomalous interactions could provide also single production of the fourth generation fermions. The anomalous single production of the fourth generation fermions is considered in a number of papers [21, 22, 23, 24]. Recently, anomalous production of the



(a)



(b)

FIG. 1: (a) The total decay width of the fourth generation down type quark and (b) the branching ratios (%) depending on the mass of the quark.

fourth generation charged lepton and neutrino at future ep colliders is considered in [25] and [26], respectively. This paper is devoted to study the anomalous single production of the fourth generation up and down type quarks at the LHC.

In section II the Lagrangian for SM and the anomalous interactions of the fourth generation quarks is presented; the decay width and branching ratios of the fourth generation quarks are evaluated. Productions of the fourth generation quarks at the LHC are studied in section III: $pp \rightarrow d_4 X \rightarrow b\gamma X$ (and its h.c.) and $pp \rightarrow u_4 X \rightarrow bW^+ X \rightarrow b\nu\ell^+ X$ processes as well as their SM backgrounds are considered. The statistical significance of the signal and achievable values of anomalous coupling strength are given with concluding remarks in Section IV.

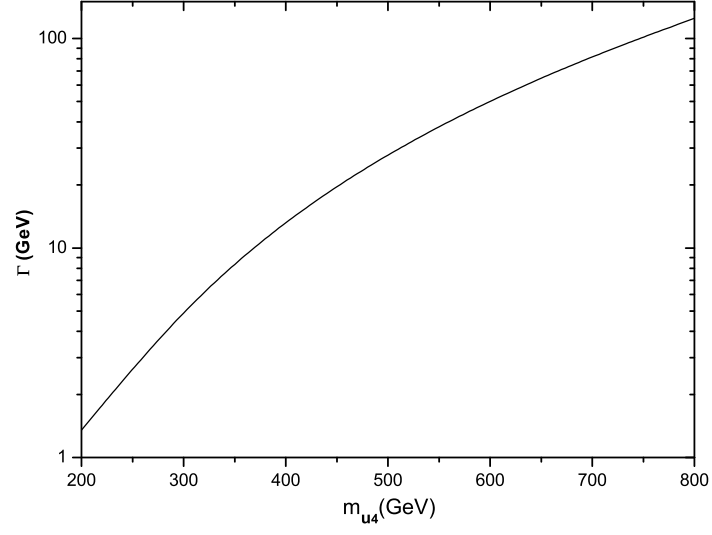
II. ANOMALOUS INTERACTIONS OF THE FOURTH GENERATION QUARKS

The effective Lagrangian for the anomalous interactions of u_4 and d_4 quarks can be rewritten from [22, 27] with minor modifications as:

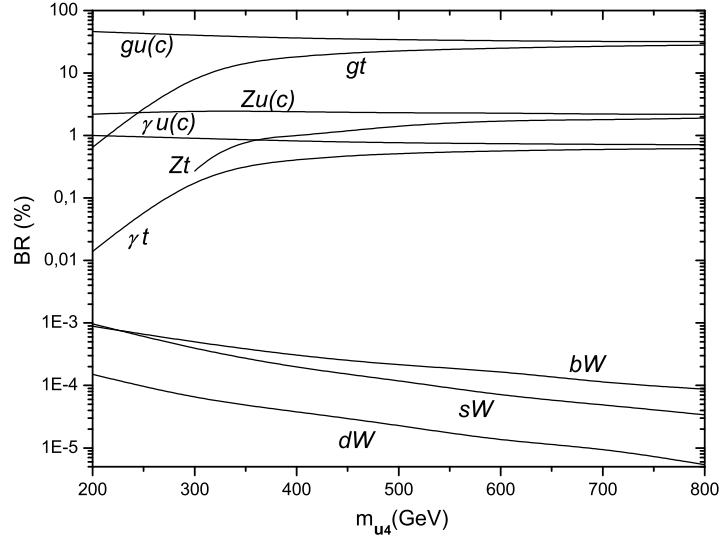
$$\mathcal{L} = \left(\frac{\kappa_\gamma^{q_i}}{\Lambda}\right) e_q g_e \bar{q}_4 \sigma_{\mu\nu} q_i F^{\mu\nu} + \left(\frac{\kappa_Z^{q_i}}{2\Lambda}\right) g_Z \bar{q}_4 \sigma_{\mu\nu} q_i Z^{\mu\nu} + \left(\frac{\kappa_g^{q_i}}{\Lambda}\right) g_s \bar{q}_4 \sigma_{\mu\nu} T_a q_i G_a^{\mu\nu} + h.c. , \quad (1)$$

where $i = 1, 2, 3$ denotes the generation index. $\kappa_\gamma^{q_i}$, $\kappa_Z^{q_i}$ and $\kappa_g^{q_i}$ are the anomalous couplings for the electromagnetic, weak (neutral current) and strong interactions, respectively (in numerical calculations, $\kappa_\gamma^{q_i} = \kappa_Z^{q_i} = \kappa_g^{q_i}$ is assumed). Λ is the cutoff scale for the new physics and e_q is the quark charge. g_e , g_Z and g_s are the electroweak and strong coupling constants. In the above equation, $\sigma_{\mu\nu} = i(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)/2$. $F^{\mu\nu}$, $Z^{\mu\nu}$ and $G_a^{\mu\nu}$ are the field strength tensors of the photon, Z boson and gluons, respectively. T_a is the Gell-Mann matrices.

Obviously new interactions will lead to additional decay channels of the fourth generation quarks. In order to compute decay widths, I have implemented the new interaction vertices into the CompHEP [28]. While calculating the SM decay contributions, CKM mixings given in Ref. [12] are used. However, CKM Matrices are not given excluding the fourth generation quark mass values of 400 GeV and 800 GeV in Ref. [12]. Therefore, CKM matrix elements for other mass values are obtained by using the same parametrization to be consistent on the rest of calculations. SM decay widths are proportional to $|V_{q_4 q'}|^2$. Depending on relative magnitudes of (κ/Λ) and $|V_{q_4 q'}|$, SM or anomalous decays will dominate. The total decay



(a)



(b)

FIG. 2: (a) The total decay width of the fourth generation up type quark and (b) the branching ratios (%) depending on the mass of the quark.

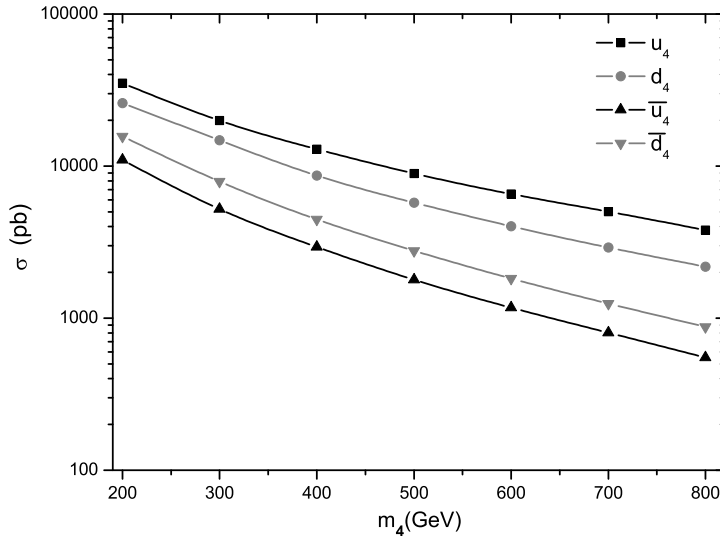


FIG. 3: The total production cross-sections of the $pp \rightarrow u_4(\bar{u}_4)X$ and $pp \rightarrow d_4(\bar{d}_4)X$ processes at the LHC.

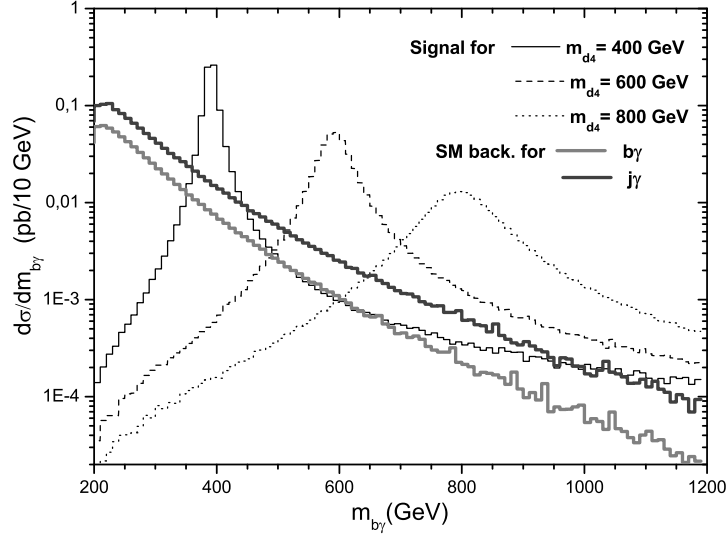
width Γ of the fourth generation quarks and the relative branching ratios are presented in Fig. 1 and Fig. 2 for $(\kappa/\Lambda) = 1 \text{ TeV}^{-1}$. Concerning the anomalous coupling strength, the value $(\kappa/\Lambda) = 1 \text{ TeV}^{-1}$ is rather conservative (the mass scale is order of electroweak scale). Consequently, I have used this value at rest of my calculations.

III. ANOMALOUS SINGLE PRODUCTION OF THE FOURTH GENERATION QUARKS AT LHC

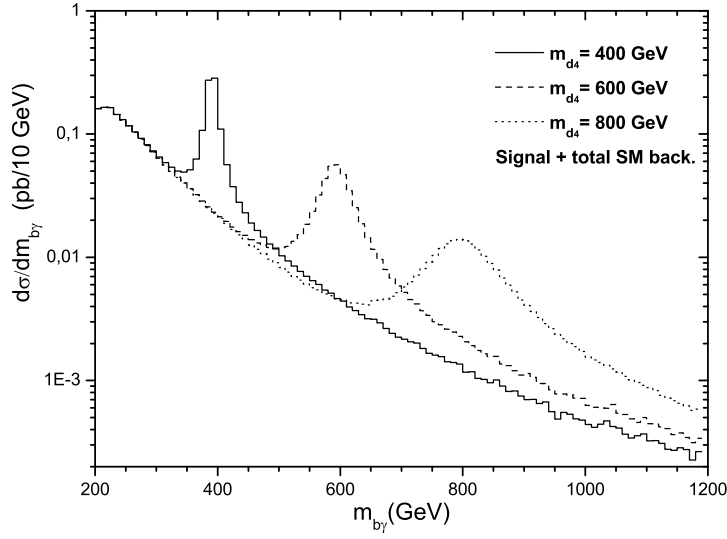
I have calculated the anomalous single production cross sections of the fourth SM generation quarks at the LHC using CompHEP with CTEQ6L1 parton distribution functions [29]. Contributions to single production of u_4 come from gu and gc processes. Similar contributions for $pp \rightarrow d_4X$ come from processes of gd , gs and gb . The results are shown in Fig. 3 for $(\kappa/\Lambda) = 1 \text{ TeV}^{-1}$.

Various signatures for anomalous interactions of the fourth generation quarks might be considered. One can group these signatures as

- Anomalous production followed by anomalous decay such as $pp \rightarrow d_4X \rightarrow gbX$,



(a)



(b)

FIG. 4: Invariant mass distributions of the fourth generation down type quark signal for three selected mass values and corresponding SM backgrounds at the LHC (with cut Selection3 given in Table I): (a) separated and (b) summed.

TABLE I: Cut selection criteria and corresponding signal and SM background cross sections for $pp \rightarrow d_4 X \rightarrow b\gamma X$ process (and its h.c.) (at $(\kappa/\Lambda) = 1\text{TeV}^{-1}$)

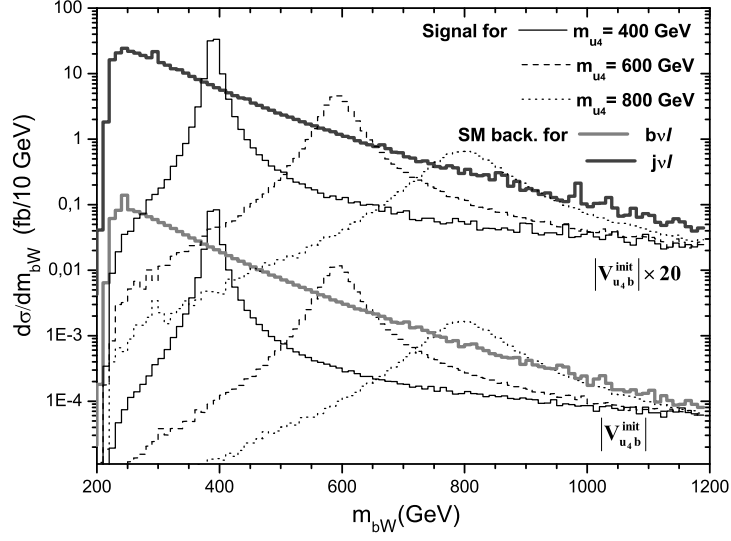
$m_{d_4}(\text{GeV})$	Signal cross sections (pb)		
	Selection1	Selection2	Selection3
	$P_T^\gamma > 20 \text{ GeV}$	$P_T^\gamma > 20 \text{ GeV}, P_T^j > 100 \text{ GeV},$ $ \eta_{j,\gamma} < 2.5, \Delta R_{j,\gamma} > 0.4$	Selection2 + b-tag + mistag
300	38.54	22.89	12.82
400	22.26	16.12	9.03
500	14.49	11.36	6.36
600	9.93	8.19	4.58
700	7.08	6.03	3.38
800	5.19	4.52	2.53
Process	SM background cross sections (pb)		
$pp \rightarrow b\gamma X + h.c.$	5.60×10^3	1.25×10^1	7.01
$pp \rightarrow c\gamma X + h.c.$	3.42×10^4	7.96×10^1	7.96
$pp \rightarrow j_{light}\gamma X$	1.58×10^5	2.83×10^2	2.83
Total	1.98×10^5	3.75×10^2	17.80

$pp \rightarrow d_4 X \rightarrow ZbX, pp \rightarrow d_4 X \rightarrow \gamma bX, pp \rightarrow u_4 X \rightarrow gtX$ and $pp \rightarrow u_4 X \rightarrow \gamma tX$

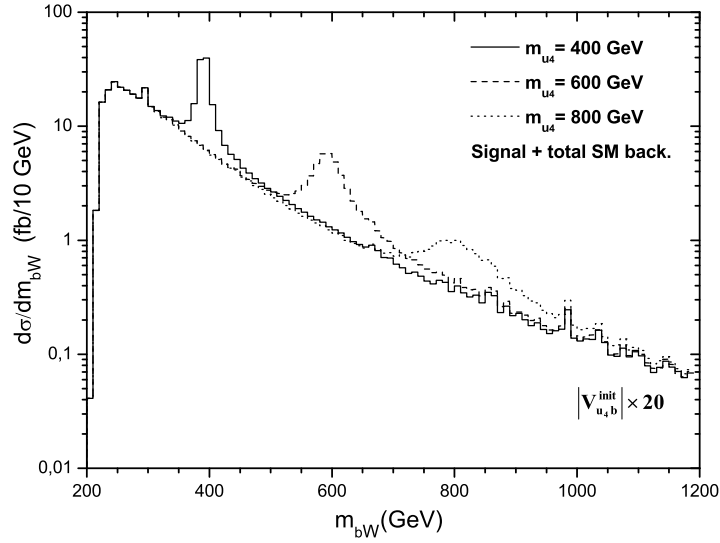
- Anomalous production followed by SM decay such as $pp \rightarrow u_4 X \rightarrow bW^+ X$ and $pp \rightarrow d_4 X \rightarrow tW^- X$.

In this study, one process is chosen from each group of signatures. Namely, $pp \rightarrow d_4 X \rightarrow \gamma bX$ from "anomalous production-anomalous decay" group and $pp \rightarrow u_4 X \rightarrow bW^+ X$ from "anomalous production-SM decay" group are chosen to investigate in details because of their relative simplicity. While the cross section of the first group is proportional with $(\kappa/\Lambda)^4$, the cross section of the second group is proportional with $(\kappa/\Lambda)^2$ and $|V_{u_4 b}|^2$. Therefore, values of (κ/Λ) and $|V_{u_4 b}|$ determine which group of signature is important for the observability.

First, $pp \rightarrow d_4 X \rightarrow b\gamma X$ process (and its h.c.) is considered as signature of anomalous interactions of the fourth generation down type quark. The SM background for this process is potentially much larger than the signal. However, some kinematic cuts have been applied



(a)



(b)

FIG. 5: Invariant mass distributions of the fourth generation up type quark signal for some mass and $|V_{u_4 b}|$ values and corresponding SM backgrounds at the LHC (with cut Selection1 given in Table II and b -tag + mistag): (a) separated and (b) summed.

TABLE II: Cut selection criteria for $pp \rightarrow u_4 X \rightarrow b\nu\ell^+ X$ process

Selection1	Selection2	Selection3
$P_T^\ell > 10\text{GeV}$	Selection1+	Selection2+
$P_T^j > 100\text{GeV}$	$ M_{j\nu\ell} - M_{u_4} < 2\Gamma_{Tot}$	b-tag+
$ \eta_{j,\ell} < 2.5$		mistag
$\Delta R_{j,\ell} > 0.4$		

in order to extract the signal and to suppress the SM background. The following selection of cuts is chosen: $P_T > 20$ GeV for photon, $P_T > 100$ GeV for all jets; $|\eta_{j,\gamma}| < 2.5$, where η denotes pseudorapidity; a minimum separation of $\Delta R = [(\Delta\phi)^2 + (\Delta\eta)^2]^{1/2} > 0.4$ (ϕ is the azimuthal angle) between the photon and jets. In addition, I assume that b -quark jet is tagged with efficiency of 56%. Moreover, 1% of light jets (for u , d , s , \bar{u} , \bar{d} , \bar{s} and g) and 10% of c -quark jets are mistagged as b -jet. The calculated signal and SM background cross sections before and after all these cuts, are given in Table I. Figure 4 shows the invariant mass distribution for the signal and the SM background for sample values of the fourth generation quark masses of 400, 600 and 800 GeV.

Second I study $pp \rightarrow u_4 X \rightarrow bW^+ X$ process at the LHC as signature of anomalous interactions of the fourth generation up type quark, followed by leptonic decay of W^+ boson ($\ell = e^+, \mu^+$). Computations show that the signal cross section for Selection3 given in Table II spans between 2.12 fb for $m_4 = 300$ GeV and 0.13 fb for $m_4 = 800$ GeV. Naturally, these values are too small with respect to the background as can be seen from Fig. 5. Main reason for the low values of the signal cross section is the initial mixing value between u_4 and b given by parametrization used. In the parametrization, $|V_{u_4 b}^{init}|$ takes values from 0.0017 for $m_4 = 300$ GeV to 0.0008 for $m_4 = 800$ GeV. Without experimental data it is not possible to know the correct CKM matrix. Therefore, $|V_{u_4 b}|$ might be bigger than $|V_{u_4 b}^{init}|$ of the parametrization. As earlier mentioned, SM decays are dependent on CKM matrix element. In this paper, the signal cross section values are computed with $|V_{u_4 b}| = |V_{u_4 b}^{init}| \times 6$, $|V_{u_4 b}^{init}| \times 10$ and $|V_{u_4 b}^{init}| \times 20$ for illustration and given in Table III for different cut selection criteria given in Table II.

The SM background for this process is studied in detail. In order to extract the signal and to suppress the SM background, some kinematic cuts are tried. These cut selection

TABLE III: Signal and SM background cross sections for $pp \rightarrow u_4 X \rightarrow b\nu\ell^+ X$ process with cut selections given in Table II (at $(\kappa/\Lambda) = 1\text{TeV}^{-1}$)

Selection	Signal cross sections (pb)						
Criterion	$ V_{u_4b} $	300 GeV	400 GeV	500 GeV	600 GeV	700 GeV	800 GeV
Selection1	$6 \cdot \left V_{u_4b}^{init}\right $	$1.36 \cdot 10^{-1}$	$8.71 \cdot 10^{-2}$	$4.82 \cdot 10^{-2}$	$3.11 \cdot 10^{-2}$	$1.65 \cdot 10^{-2}$	$1.03 \cdot 10^{-2}$
	$10 \cdot \left V_{u_4b}^{init}\right $	$4.64 \cdot 10^{-1}$	$2.43 \cdot 10^{-1}$	$1.34 \cdot 10^{-1}$	$8.69 \cdot 10^{-2}$	$4.04 \cdot 10^{-2}$	$2.86 \cdot 10^{-2}$
	$20 \cdot \left V_{u_4b}^{init}\right $	1.86	$9.71 \cdot 10^{-1}$	$5.36 \cdot 10^{-1}$	$3.48 \cdot 10^{-1}$	$1.83 \cdot 10^{-1}$	$1.15 \cdot 10^{-1}$
Process	SM background cross sections(pb)						
$pp \rightarrow b\nu\ell^+X$	0.23						
$pp \rightarrow j_{light}\nu\ell^+X$	$1.31 \cdot 10^3$						
$pp \rightarrow c\nu\ell^+X$	$1.69 \cdot 10^2$						
Total	$1.48 \cdot 10^3$						
	Signal cross sections (pb)						
Selection2	$6 \cdot \left V_{u_4b}^{init}\right $	$1.11 \cdot 10^{-1}$	$7.25 \cdot 10^{-2}$	$4.00 \cdot 10^{-2}$	$2.56 \cdot 10^{-2}$	$1.36 \cdot 10^{-2}$	$8.67 \cdot 10^{-3}$
	$10 \cdot \left V_{u_4b}^{init}\right $	$3.78 \cdot 10^{-1}$	$2.01 \cdot 10^{-1}$	$1.11 \cdot 10^{-1}$	$7.15 \cdot 10^{-2}$	$3.79 \cdot 10^{-2}$	$2.41 \cdot 10^{-2}$
	$20 \cdot \left V_{u_4b}^{init}\right $	1.51	$8.07 \cdot 10^{-1}$	$4.44 \cdot 10^{-1}$	$2.86 \cdot 10^{-1}$	$1.52 \cdot 10^{-1}$	$9.64 \cdot 10^{-2}$
Process	SM background cross sections(pb)						
$pp \rightarrow b\nu\ell^+X$	$1.11 \cdot 10^{-3}$						
$pp \rightarrow j_{light}\nu\ell^+X$	7.31						
$pp \rightarrow c\nu\ell^+X$	0.96						
Total	8.27						
	Signal cross sections (pb)						
Selection3	$6 \cdot \left V_{u_4b}^{init}\right $	$6.21 \cdot 10^{-2}$	$4.06 \cdot 10^{-2}$	$2.24 \cdot 10^{-2}$	$1.44 \cdot 10^{-2}$	$7.63 \cdot 10^{-3}$	$4.86 \cdot 10^{-3}$
	$10 \cdot \left V_{u_4b}^{init}\right $	$2.12 \cdot 10^{-1}$	$1.13 \cdot 10^{-1}$	$6.22 \cdot 10^{-2}$	$4.00 \cdot 10^{-2}$	$2.12 \cdot 10^{-2}$	$1.35 \cdot 10^{-2}$
	$20 \cdot \left V_{u_4b}^{init}\right $	$8.47 \cdot 10^{-1}$	$4.52 \cdot 10^{-1}$	$2.49 \cdot 10^{-1}$	$1.60 \cdot 10^{-1}$	$8.49 \cdot 10^{-2}$	$5.40 \cdot 10^{-2}$
Process	SM background cross sections(pb)						
$pp \rightarrow b\nu\ell^+X$	$6.22 \cdot 10^{-4}$						
$pp \rightarrow j_{light}\nu\ell^+X$	$7.31 \cdot 10^{-2}$						
$pp \rightarrow c\nu\ell^+X$	$9.62 \cdot 10^{-2}$						
Total	$1.70 \cdot 10^{-1}$						

TABLE IV: Statistical significances (SS) for anomalous interactions of the fourth generation up and down type quarks at the LHC with integrated luminosity of 100 fb^{-1}

$m_4 \text{ (GeV)}$	$SS \text{ for } pp \rightarrow d_4 X \rightarrow b\gamma X$	$SS \text{ for } pp \rightarrow u_4 X \rightarrow b\nu\ell^+ X$		
		$6 \cdot V_{u_4 b}^{init} $	$10 \cdot V_{u_4 b}^{init} $	$20 \cdot V_{u_4 b}^{init} $
300	960	82.3	230	920
400	677	41.0	114	456
500	477	24.4	68	272
600	343	17.6	49	196
700	253	9.7	27	108
800	190	6.2	17	69

criteria are listed in Table II. The calculated signal and SM background cross sections after all these selections, are presented in Table III. In Selection1, one isolated lepton (e^+ or μ^+) is identified and used as trigger. In addition, W^+ boson is reconstructed by taking the missing transverse momentum as the neutrino momentum, and is fixed the longitudinal component by M_W . The most of the contribution to background cross section comes from jets of light quarks and gluon. In Selection2, I require $|M_{j\nu\ell} - M_{u_4}| < 2\Gamma_{Tot}$, where Γ_{Tot} is given in Fig. 2a. With this cut, the background is decreased by more than a factor of 100. In Selection3, b -quark jet is tagged with efficiency of 56%, and 1% of light jets (for u , d , s , \bar{u} , \bar{d} , \bar{s} and g) and 10% of c -quark jets are mistagged as b -jet in addition to Selection2. These cuts give further decrease on SM background cross section by almost a factor of 100. In total, cut selections decrease background by a factor of 10^5 with respect to no-cut case. The calculated signal and background cross sections, are plotted in Fig. 5 as a function of the reconstructed $b\nu\ell$ invariant mass. It is drawn for some $|V_{u_4 b}|$ and mass values of the fourth generation quark for illustration.

IV. CONCLUSION

The statistical significance (SS) values, evaluated from $SS = (\sigma_S/\sqrt{\sigma_B})\sqrt{L_{int}}$, where L_{int} is the integrated luminosity of the collider, for both signal processes at the LHC with integrated luminosity of 100 fb^{-1} are presented in Table IV. Achievable values of anomalous

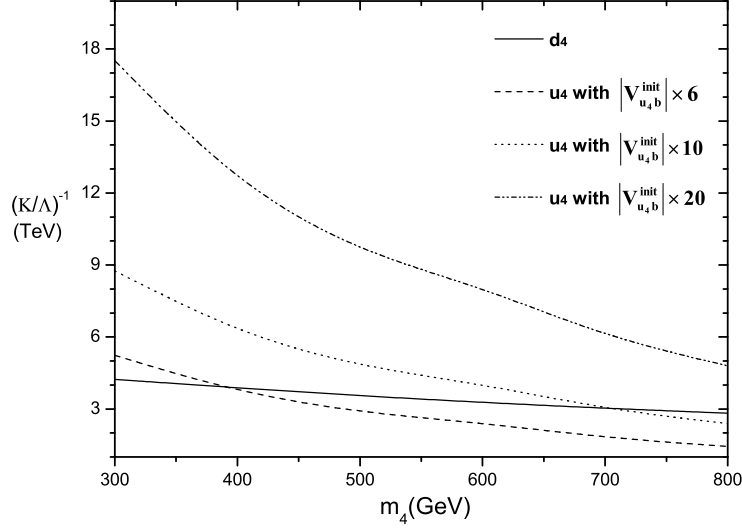


FIG. 6: Observation reach at 3σ for anomalous coupling strength as a function of the fourth generation quark mass for $pp \rightarrow u_4 X \rightarrow b\nu\ell^+ X$ and $pp \rightarrow d_4 X \rightarrow b\gamma X$ processes at the LHC.

coupling strength as a function of the fourth generation quark mass for processes under consideration are shown in Fig. 6. For both processes $SS \geq 3$ is taken as an observation criterion. One can see that values as low as 0.24 (0.35) TeV^{-1} are reachable for (κ/Λ) at $m_4 = 300$ (800) GeV for down type quark "anomalous production-anomalous decay" group process (as mentioned above). While anomalous interaction of the fourth generation up type quark is not observable with "anomalous production-SM decay" type process at $|V_{u_4b}^{init}|$, it becomes better below 400 GeV mass of u_4 for $|V_{u_4b}^{init}| \times 6$. $pp \rightarrow u_4 X \rightarrow b\nu\ell^+ X$ process for $|V_{u_4b}^{init}| \times 10$ gets more observable below 700 GeV mass of fourth generation quark compare to $pp \rightarrow d_4 X \rightarrow b\gamma X$ process. For $|V_{u_4b}^{init}| \times 20$, reachable values for (κ/Λ) are 0.057 (0.21) TeV^{-1} at $m_4 = 300$ (800) GeV for up type quark "anomalous production-SM decay" group process.

As a result of this study, possible anomalous interactions of the fourth generation quarks at the given range of the quark mass, $|V_{u_4b}|$ and (κ/Λ) will be observed or excluded at the LHC in a few years.

Acknowledgments

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